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THE ~~CHALLENGE OF~~ OUTLOOK FOR GAS-CORE NUCLEAR ROCKETS

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GENERAL CHARACTERISTICS

Performance improvement of a reaction-mass propulsion system for space rockets can be effected only by an increase in the energy content of the propellant. Thus by utilizing the propellant with the highest specific heat - hydrogen, solid-core nuclear rockets are capable of a higher specific impulse than that possible with a chemical system for a given temperature.

BOX INSERT ON PAGE 12

> A GAS-CORE REACTOR, like a solid-core reactor, for nuclear propulsion is a through-flow device; hydrogen and a fissionable gas flow into an externally moderated-reflected cavity, heat is released by nuclear fission, and the mixture of hot gases is expanded through an exhuast nozzle to produce thrust. The fissionable gas is not retained in the cavity; a constant uranium to hydrogen mass flow ratio enters and leaves the reactor. The frequently used term "separation" process denotes an increase of fuel residence time over that of the hydrogen and, correctly used, does not imply that any fuel is permanently retained in the system.

Further performance increases require a higher propellant exhaust temperature. Since the maximum propellant exhaust temperature cannot exceed that of the heat-transfer surface in a solid-core nuclear system, a fundamental change is necessary to provide a specific impulse significantly greater than the 1000 seconds associated with an advanced solid-core nuclear rocket.

A gas-core reactor offers the attractive possibility of specific impulses up to 3000 seconds. Basically, this is accomplished by maintaining the nuclear fuel in the reactor as a gas rather than as a solid. Obviously, the containing walls still impose a temperature limit on the system, but now the energy transfer to the propellant can occur at higher temperatures.

Figure 1 illustrates the fundamental gas-core concept. Hydrogen propellant and gaseous uranium 235 (or plutonium 239) are injected into an externally moderated-reflected reactor cavity. With the system under the pressure necessary to maintain a critical mass within the reactor, the nuclear heat released is transferred to the propellant either by direct molecular collisions or by thermal radiation. The heated propellant and the fissionable material are then ejected through an exhaust nozzle to produce thrust.

Although the gas-region temperature may exceed that of a solid fuel element, there is a limit resulting from the fact that all of the fission-generated heat is not transferred directly to the propellant; some is deposited in the surrounding solid regions by gamma and neutron heating and by thermal radiation to the cavity walls. For example, if 10 percent of the total enthalpy rise of the propellant must occur at a gas temperature of 5000° R or less, the maximum exhaust temperature of a constant-specific-heat propellant is limited to $50,000^{\circ}$ R. The implications of this restraint are discussed more extensively in reference 1.

Another performance limit is imposed by the required cavity pressure. For prescribed materials and reactor geometry, the atom density required for criticality is fixed. Because the nuclear fuel is a gas, the consideration of higher temperatures is directly reflected in an increased pressure requirement. Even within these limits, however, propellant exhaust temperatures of $10,000^{\circ}$ to $15,000^{\circ}$ R and specific impulses up to 3000 seconds are potentially available from such a system.

While an increase of specific impulse is certainly desirable, an overall performance advantage may not exist if it is accompanied by a decrease of reactor thrust to weight ratio. It is therefore necessary to investigate briefly the trade-off between impulse and thrust-weight ratio. This will then provide a useful evaluation criterion for proposed high-impulse systems.

Figure 2 shows the specific impulse required to perform a seven-man, 460-day Venus mission as a function of powerplant thrust to weight ratio. The reference vehicle here is an advanced solid-core nuclear rocket with a thrust to weight ratio of 50 and an impulse of 1000 seconds. These curves show the decrease in vehicle weight afforded by impulses greater than 1000 seconds; for example, a 3000-second engine with a thrust to weight ratio of 3 could perform this mission with a total vehicle weight one-half that of the solid-core system. It is also interesting to note that a 3000-second-impulse engine with a thrust-weight ratio of 10^{-2} OR LESS offers no advantage over the solid-core reference vehicle FOR THE 7-MAN VENUS MISSION SHOWN.

It is possible to utilize the advantage of high specific impulse to decrease the trip-time requirement rather than the vehicle weight. This is illustrated in figure 3 again for a seven-man Venus mission with an initial weight in orbit of 1.7 million pounds and a thrust to weight ratio greater than 10^{-1}. A gas-core reactor system with an impulse of 3000 seconds would reduce the solid-core trip-time requirement from 460 to 150 days.

This is perhaps a more significant advantage; for the same 460-day trip time, the high-impulse-system weight was less, but both vehicles still performed the same mission. For equal vehicle weight, however, the solid-core rocket cannot compete on the basis of trip time - it simply could not accomplish the mission in less than 460 days. Future information on human and system reliability factors will more clearly define the advantage, or perhaps necessity, of reduced trip-time capability.

It is apparent, then, that a gas-core nuclear rocket has a performance potential sufficiently greater than a solid-core system to warrant additional consideration. It is the purpose of gaseous reactor research to evaluate to what extent this maximum possible performance is attainable. Described herein are the various concepts currently under consideration, their unique and common problems, and the present status and future goals of the research.

CURRENT RESEARCH

Gaseous reactor research is presently concerned with providing an answer to the question: Will it work? Before discussing the specifics of this research, it will be helpful to define just what mechanisms are involved in a gas-core reactor. Basically, there are three processes at work simultaneously, as illustrated in figure 4.

First, because the system is a reactor, sufficient fissionable material must be present to maintain a chain reaction. Second, because it is a propulsion device, hydrogen propellant must flow through the reactor cavity. Fianlly, because it is a heat exchanger, the fission energy must be transferred to the hydrogen. So, hydrodynamics, heat transfer, and nucleonics in approximately that order of importance are problem areas common to any gas-core concept. All three phenomena are currently under investigation.

The hydrodynamic requirements on a gas-core reactor system are extremely severe; and consequently major attention has been focused in this direction. The problem results from the fact that the fissionable fuel flows through the reactor and is ejected with the hydrogen propellant. The ratio of the mass flow rate of hydrogen to fuel is the parameter of particular interest. One effect of exhausting fuel with the hydrogen is the reduction of specific impulse due to the resultant increase of propellant-gas average molecular weight. For example, if this flow ratio is unity, the specific impulse is reduced to 70 percent of that obtainable with pure hydrogen. This effect of molecular weight dilution is illustrated in figure 5. The curve shown is an approximation since it is based on a fuel to hdyrogen molecular weight ratio that is assumed to be constant (unaffected by dissociation and ionization). Although the curves of figure 5 would actually be pressure dependent, they are sufficient to illustrate the general effect.

A more severe limit on fuel loss is placed by economic considerations. For example, if the cost of nuclear fuel used is limited to that of the hydrogen, the fuel flow rate must be $1/35^{th}$ that of the hydrogen (ref. 2) Reference 2 also shows that uniform mixture of these proportions implies a reactor pressure of the order of 100,000 psia for criticality. Obviously, something must be done to reduce the required pressure to a reasonable level. This can be accomplished by slowing the fuel, relative to the hydrogen, as the mixture passes through the reactor. Thus, what is required is an increase of fuel residence time relative to that of the hydrogen.

This increase can be viewed as a "separation" factor S. In general, the required reactor pressure in psia is given by:

$$\frac{P}{1000} = \frac{4W'}{3S} \frac{N_F}{10^{18}} \frac{T}{10{,}000}$$

where N_F is the critical density, at/cc; T is the reactor temperature, ^{o}R; and W' is the hydrogen to fuel mass flow rate ratio. The separation factor S is the ratio of fuel to hydrogen residence time in the reactor, or, conversely, is the ratio of the average hydrogen velocity through the reactor to that of the fuel.

Although the term separation affords a convenient one-word reference to the flow process involved, it must be used with care. It does not imply that some fuel is separated and retained in the system, but rather that the fuel atoms follow a separate, or different, path through the reactor so that the fuel residence time is greater than that of hydrogen.

A feasible gas-core system must provide a separation factor of the order of 100. Fluid-mechanical or external body forces have been considered as means to this end.

Two proposed schemes that utilize hydrodynamic forces to accomplish the fuel hold-up, or "separation," are (1) a vortex (refs. 3 and 4) and (2) a coaxial flow system (ref. 5), ~~hath~~ BOTH illustrated in figure 6. The vortex system proposes to achieve separation as a result of pressure diffusion that tends to create a high-density annular fuel region through which the propellant must diffuse. Physically, the process can be pictured as a centrifugal one in which the heavy fuel atoms are thrown radially outward; this effect is opposed by the incoming gas flow that tends to carry them radially inward. The primary difficulty here is that the large hydrogen flow rates required for high thrust tend to diminish the separation process. Analysis suggests that to alleviate this problem the system should be composed of many parallel vortices placed in a tube bundle (ref. 3) or a single-cavity matrix (ref. 6) The effects of turbulence (refs. 6 and 7) and end-wall boundary-layer flow (ref. 8) in a vortex system have been studied.

Where the vortex attempts to separate a fuel-propellant mixture, the coaxial flow system is aimed at maintaining an initial separation. In this configuration, the fuel is injected with a low velocity into a surrounding fast-moving propellant stream. Although the fuel stream is accelerated by diffusion and momentum transfer as it moves through the reactor cavity, the average fuel residence time is greater than that of the hydrogen. A turbulent coaxial flow system is currently under investigation at the NASA Lewis Research Center.

Other gas-core concepts that have been suggested are: (1) a plasma core (ref. 9), which employs electromagnetic forces to maintain separation, and (2) a "glo-plug" system (ref. 10), which proposes complete fuel containment within transparent tubes. The plasma-core concept must entertain extremely large magnetic-field strengths, and a glo-plug system faces serious materials requirements.

Because propellant temperatures (10,000° to 30,000° R) well above the melting point of solid materials must be contained within a reactor cavity, any gas-core system incurs severe thermal radiation problems. If all of the nuclear heat released is radiated to the reactor wall, propellant temperatures obviously cannot exceed that of a solid-core reactor, and the performance advantage is lost. Some concepts, such as the coaxial flow, plasma core, and glo-plug, depend to a large extent on thermal radiation to transfer energy to the propellant. This necessarily implies a propellant that is opaque to thermal radiation.

Two conflicting requirements now exist:

(1) The propellant must be hydrogen. (Hydrogen is transparent below about 12,000° R).

(2) The propellant must be opaque.

This ineluctable situation can be resolved by adding a material to the hydrogen to render it opaque. Solid particles, mists, and other gases are the possible choices. Reference 11 reports some transmissivity MEASUREMENTS of room temperature particle dispersions and concludes that solid-particle seeding appears to be a possiblility. Other aspects of thermal radiation have been investigated (refs. 12, 13, and 14) but much remains to be done.

Though some of the nucleonic characteristics are obviously unique, reactor criticality does not appear to impose any severe constraints on a gaseous reactor system. A two-dimensional diffusion study of a gas-core reactor presented in reference 15 contains an analysis of the effect of pertinent geometry, materials, and temperature factors on critical mass.

Since essentially all nucleonic work to date has been of an analytical nature, the value of critical and subcritical experiments is apparent. The only use known to this author of a gaseous nuclear fuel in a critical assembly is the Russian reactor reported in reference 16. Though the fissionable material UF_6 was a gas, the reactor was not a "cavity" reactor; the moderation was accomplished by a beryllium matrix within an external graphite reflector. That reference reports experimental evidence which suggests that gaseous fueled reactors possess an inherent control advantage that can be exploited by providing an external volume into which the nuclear fuel can expand as the temperature is increased. Reference 17 describes a cavity-reactor critical experiment in which solid-fuel foil was externally moderated-reflected with heavy water. Fair agreement between diffusion theory and experiment is reported in reference 18 for a polonium-beryllium source in a graphite-reflected cavity.

Status and Future Goals

At present, the bulk of gas-core reactor research is directed toward the flow process. Analytical and experimental studies are being conducted on two-component isothermal flow systems of; for example, air and bromine. The basic analyses utilize the more rigorously understood laminar-flow relations, but turbulence is recognized as the more likely flow regime. Laminar results are therefore modified, somewhat empirically, and experimental studies are used to check the validity of the procedure (ref. 2). Though much remains unknown, preliminary performance estimates have been made and, within the limits of the necessary assumptions, the results appear promising.

A two-dimensional gray-gas thermal radiation analysis (ref. 14) carried out at Lewis indicates that optical thicknesses of the order 10 are required to prevent excessive radiant heating of the wall in gas-core reactors. A system of such opacity would absorb 99.995 percent of incident radiation, transmitting only 0.005 percent. Such an apparently extreme condition can be obtained by seeding hydrogen WITH approximately 1 percent by weight ~~with~~ of carbon dust, based on values reported in reference 11. Such an estimate, however, is restricted to a rather narrow range of conditions and serves mainly to indicate the need for more information.

Obviously, solid-particle seeding is not the complete answer, because the sublimation would occur within the reactor for contemplated exhaust temperatures of 10,000° to 20,000° R. Materials such as cesium and lithium have also been suggested as possible seeding materials. The overall problem of radiative heat transfer to seeded hydrogen is quite complicated and further work is necessary. This is particularly true with regard to chemical interaction between the hydrogen and seeding material and the optical properties of the resulting chemical species.

Some analytical information is available on the optical absorption properties of hydrogen gas, but little or no experimental data exist in the temperature range of 5000° to 30,000° R and for pressures from 1 to 300 atmospheres. Analytical and experimental studies of the absorptivity of possible seeding materials are also needed. For a gas-core reactor, the exhaust-nozzle-cooling problem is considerably more complex than for conventional systems. In addition to conduction heat transfer, thermal radiation from the hot exhaust gases will further complicate nozzle cooling. To date, this problem has received little attention.

The reactor criticality information available is sufficient for system performance estimated, but additional work will be required for specific configurations and operating conditions. The applicability of diffusion theory to cavity reactors has been relatively unexplored because of a lack of existing experimental information. Computational difficulties have prevented any extensive comparison of transport and diffusion methods for gas-core configurations. Effects on reactor criticality of fuel and moderator density gradients and gamma and neutron heating have not been investigated to any extent.

The performance potential of gaseous reactors far exceeds the best envisioned for solid-core heat-transfer rockets. To what extent this potential can in fact be realized is not presently known. Results of research studies are sufficiently promising to justify further work in this field. Even when treated separately, the hydrodynamic, heat transfer, and nucleonic processes are difficult to analyze. Recognition of their mutual dependency will introduce additional complexities, but is necessary for a realistic understanding of system performance. This is the next major goal of current gas-core research. It is an effort that is both useful and necessary, and, hopefully, one that will lead to a new generation of nuclear rockets.

REFERENCES

1. Meghreblian, Robert V.: Performance Potential of Nuclear Rockets. TR 34-96, Jet Prop. Lab., C.I.T., July 1960.

2. Rom, Frank E., and Ragsdale, Robert G.: Advanced Concepts for Nuclear Rocket Propulsion. Paper 44, NASA Univ. Symposium, Chicago (Ill.), Nov. 1962.

3. Kerrebrock, Jack L., and Meghreblian, Robert V.: Vortex Containment for the Gaseous-Fission Rocket. TR 34-205, Jet Prop. Lab., C.I.T., Sept. 1961.

4. Ragsdale, Robert G.: NASA Research on the Hydrodynamics of the Gaseous Vortex Reactor. NASA TN D-288, 1960.

5. Weinstein, Herbert, and Ragsdale, Robert G.: A Coaxial Flow Reactor - A Gaseous Nuclear-Rocket Concept. Preprint 1518-60, ARS, Dec. 1960.

6. Rosenzweig, Martin L., Lewellen, W. S., and Kerrebrock, J. L.: The Feasibility of Turbulent Vortex Containment in the Gaseous Fission Rocket. Preprint 1516 A-60, ARS, Dec. 1960.

7. Ragsdale, Robert G.: Applicability of Mixing Length Theory to a Turbulent Vortex System. NASA TN D-1051, 1961.

8. Kendall, James M., Jr.: Experimental Study of a Compressible, Viscous Vortex. TR 32-290, Jet Prop. Lab., C.I.T., June 1962.

9. Spencer, D. F.: Thermal and Criticality Analysis of the Plasma Core Reactor. TR 32-189, Jet Prop. Lab., C.I.T., Jan. 1962.

10. Anon.: A Summary of ~~Douglas~~ DOUGLAS Research in Advanced Propulsion Systems. Rep. SM-41961, Douglas Aircraft Co., Inc., June 1962.

11. Lanzo, Chester D., and Ragsdale, Robert G.: Experimental Determination of Spectral and Total Transmissivities of Clouds of Small Particles. NASA TN D-1405, 1962.

12. Patch, Richard W.: Methods for Calculating Radiant Heat Transfer in High Temperature Hydrogen Gas. Rep. M-1492-1, United Aircraft Corp., Nov. 1961.

13. Meghreblian, Robert V.: Thermal Radiation in Gaseous Fission Reactors for Propulsion. TR 32-139, Jet Prop. Lab., C.I.T., July 1961.

14. Einstein, Thomas H.: Radiant Heat Transfer to Absorbing Gases Enclosed in a Circular Pipe with Conduction, Flow, and Internal Heat Generation. NASA TR R-156, 1963.

15. Hyland, Robert E., Ragsdale, Robert G., and Gunn, Eugene J.: Two-Dimensional Criticality Calculations of Gaseous-Core Cylindrical Cavity Reactors. NASA TN D-1575, 1963.

16. Kikoin, I. K., et al.: Experimental Reactor with Gaseous Fissionable Substance (UF_6). Soviet Jour. Atomic Energy, vol. 5, no. 3, Sept. 1958, pp. 1167-1175.

17. Paxton, H. C., and Orndoff, J. D.: Group N-2 Progress Report for October 21-November 20, 1960, Los Alamos Scientific Laboratory.

18. Fox, Thomas A., Shook, Donald F., Mueller, Robert A., and Fieno, Daniel: Experimental Neutron Flux Distributions in a Graphite Assembly with an Internal Cavity. NASA TN D-1460, 1962.

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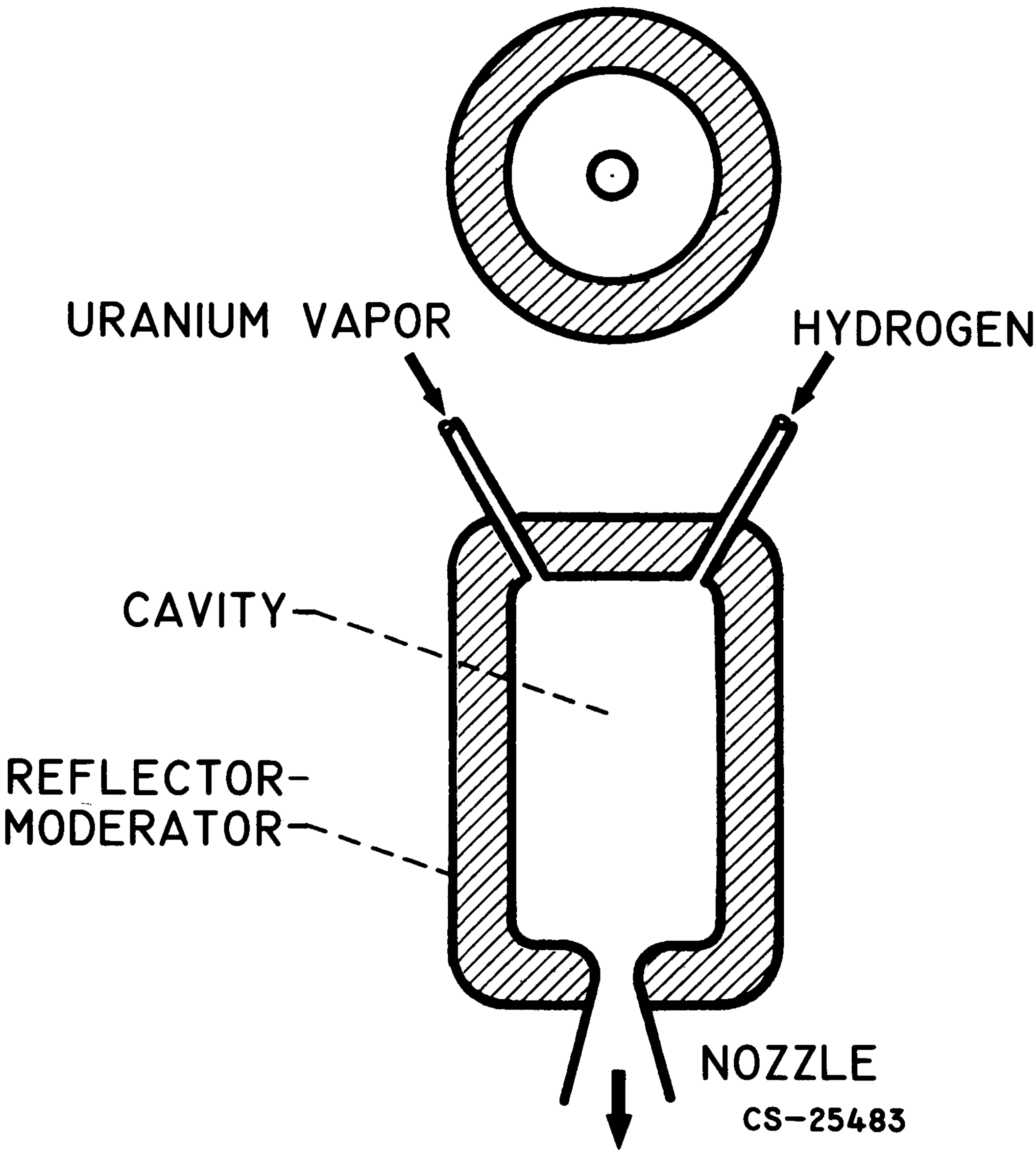

Figure 1. - Gaseous cavity reactor.

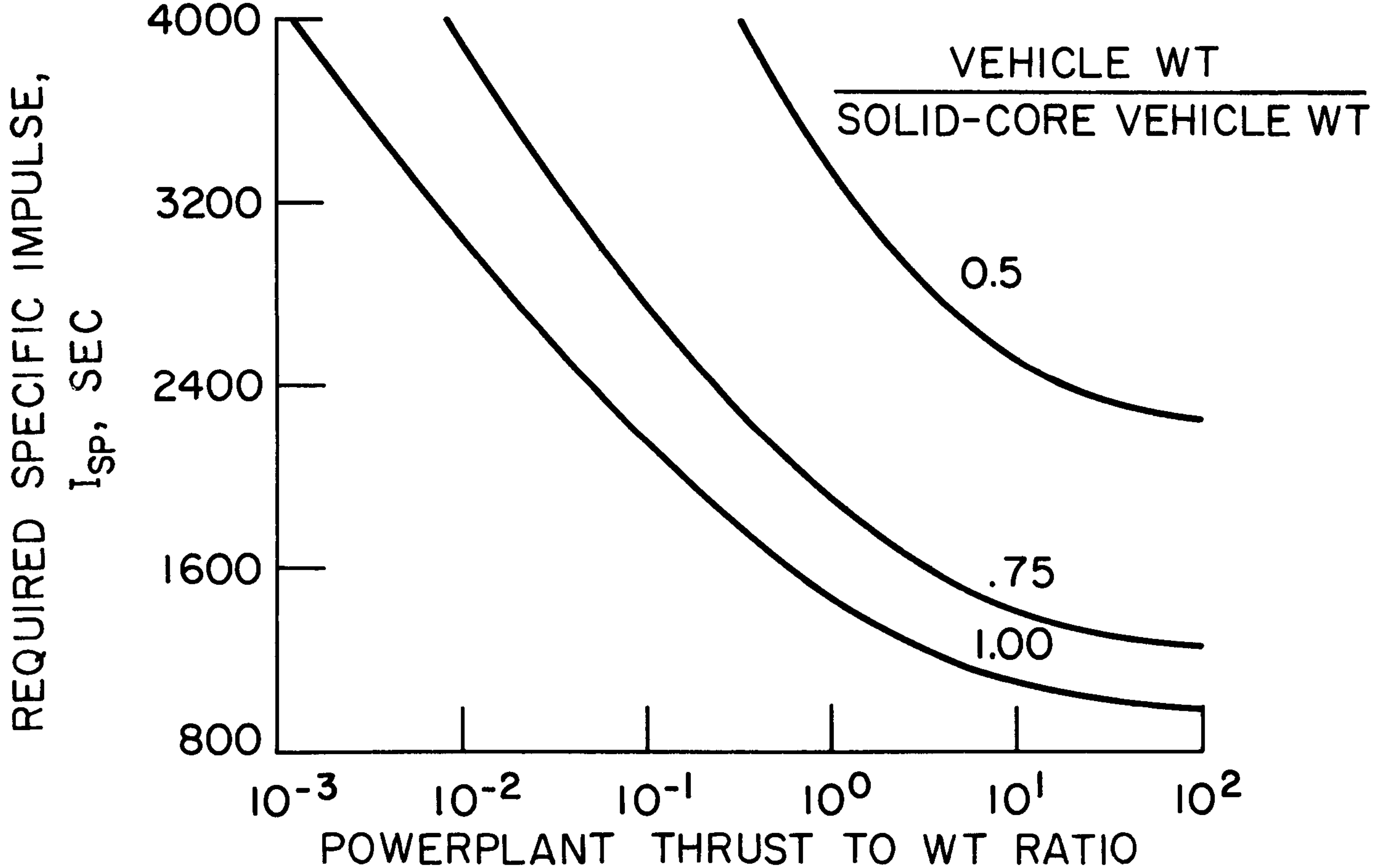

Figure 2. - Effect of powerplant thrust to weight ratio on specific impulse requirement for a seven-man 460 day Venus mission.

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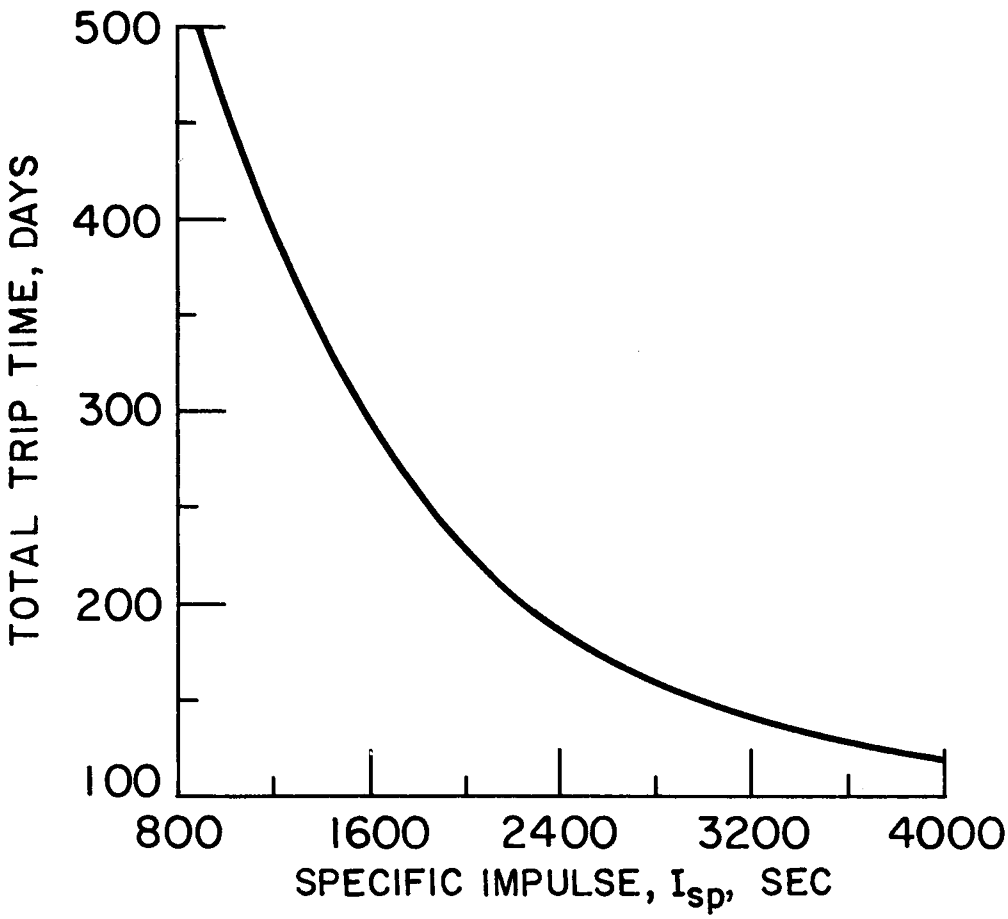

Figure 3. - Effect of specific impulse on mission time for a seven-man Venus mission. Initial weight in orbit, 1.7×10^6 lb; thrust per powerplant weight, $>10^{-1}$.

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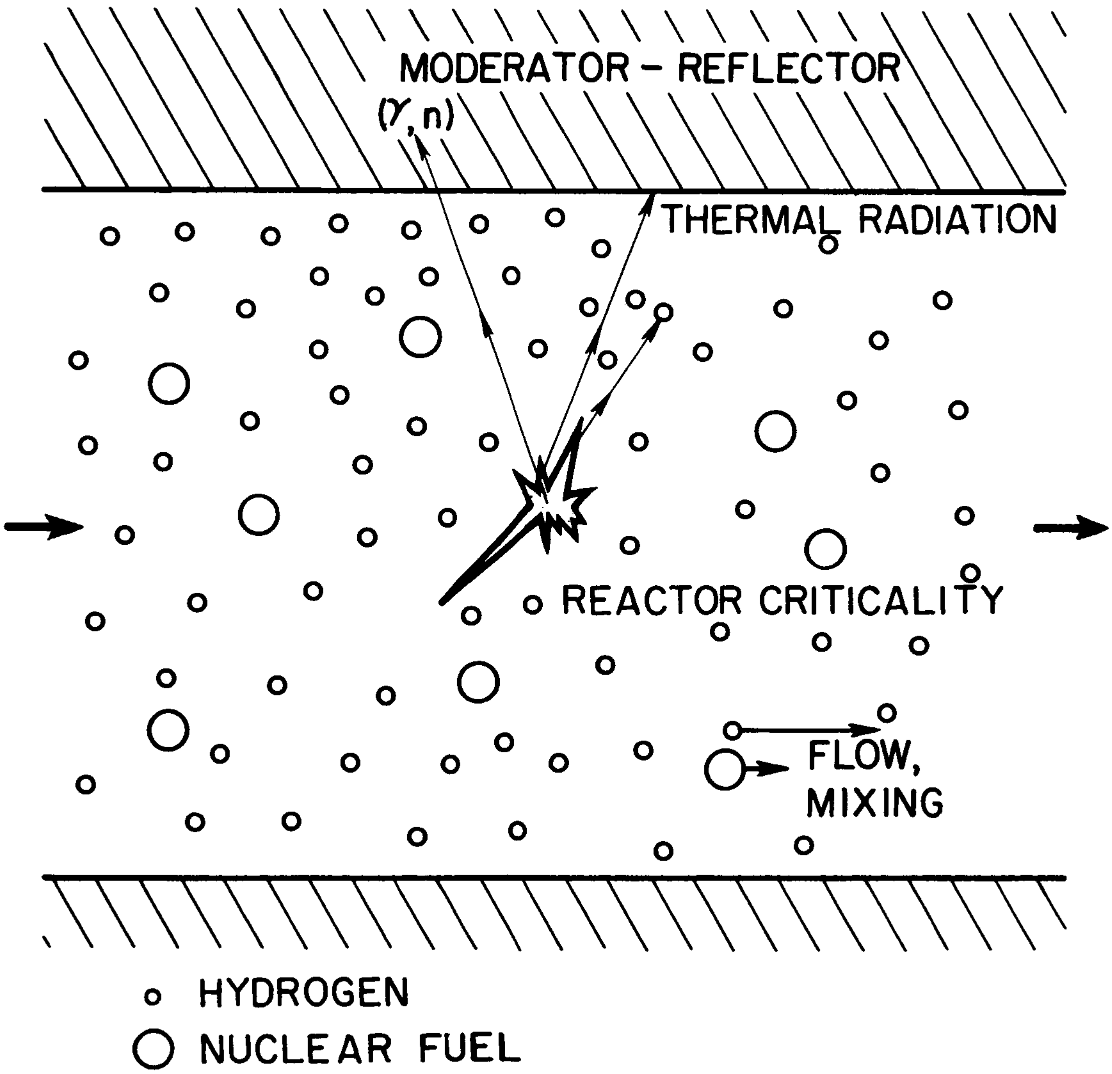

Figure 4. - Fundamental gaseous reactor processes.

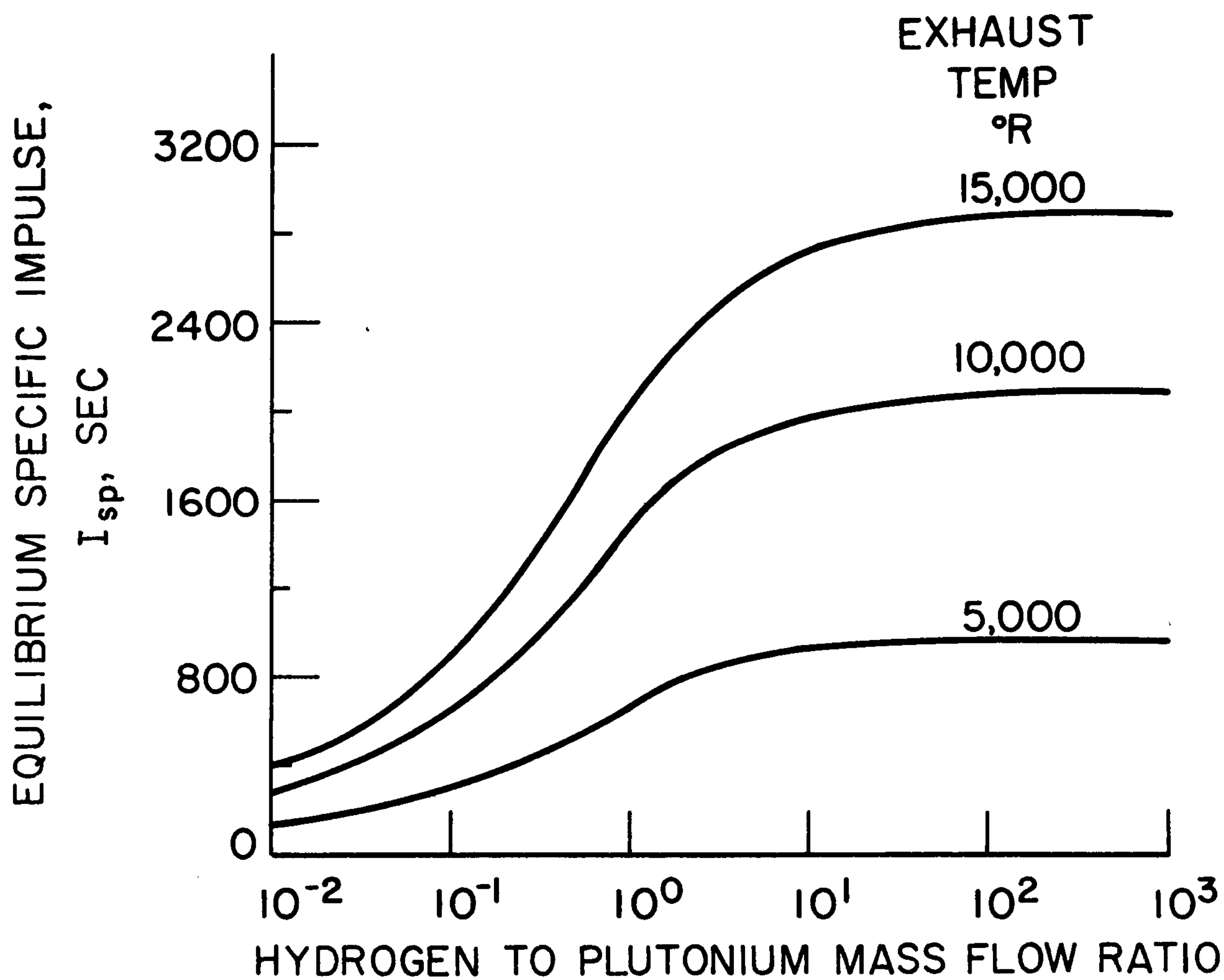

Figure 5. - Plutonium dilution effect on hydrogen specific impulse for plutonium-hydrogen molecular weight ratio, M_{pu}/M_{H_2} = 239/2, and pressure greater than 100 atm.

(Capital P)

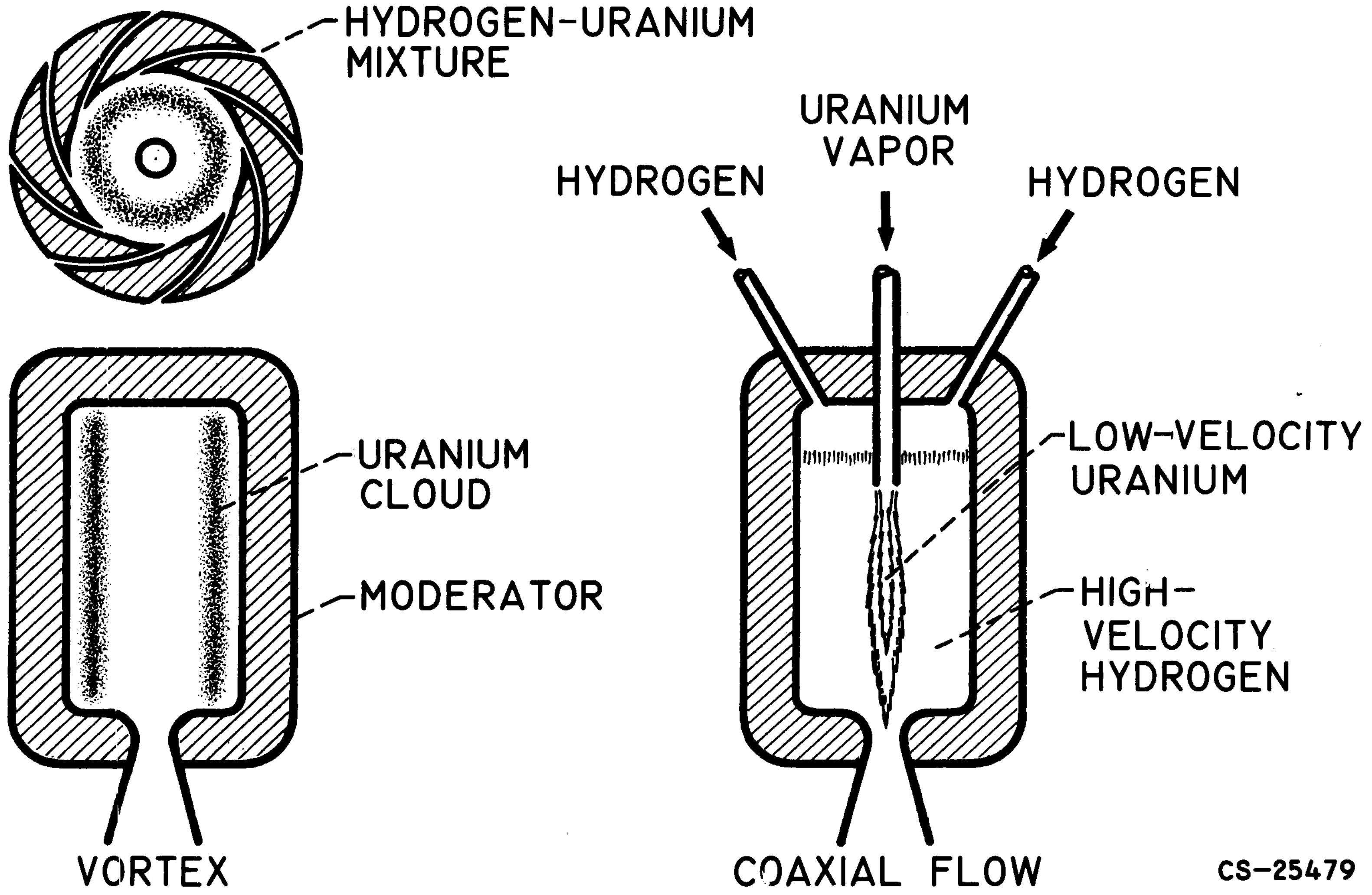

Figure 6. - Gaseous cavity reactor concepts.